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Pulsars are born as magnetars

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Abstract. This paper suggests the idea that all neutron stars experienced at birth an ultrafast decay of their magnetic fields from their initial values to their current surface values. If the electromagnetic energy radiated during this field decay is converted into kinetic energy of the neutron star via the radiation reaction mechanism then the decay time is of the order of 10^{-4} s provided that the initial magnetic fields lie in the range of $10^{14} - 10^{16}$ G. This means that all neutron stars are born with magnetic fields typical of magnetars. According to this model the neutron stars acquire their observed high space velocities during the birth ultrafast decay of their magnetic fields. The origin of this field decay points to magnetic instabilities occurring at the end of the birth process.

1. Introduction

The neutron stars PSR J2144–3933 and SGR 0418+5729 have strongly called attention because their respective periods $P = 8.5$ s and $P = 9.1$ s are typical of magnetars but their respective magnetic fields $B_s = 1.9 \times 10^{12}$ G and $B_s = 7.5 \times 10^{12}$ G are typical of radio pulsars (Tiengo et al 2011; Rea et al. 2010). This seems to indicate that both pulsars were born as magnetars, but their magnetic fields decayed to intensities typical of radio pulsars. This paper suggests that this decay was ultrafast and occurred during the birth of these stars. More generally, this paper suggests the idea that all neutron stars at birth experienced an abrupt exponential decay of their magnetic fields from their initial values B_0 to their current surface values B_s . The nascent neutron stars then radiated electromagnetic energy during the specific time τ_s . If this radiative energy is converted into kinetic energy then the time τ_s is shown to be of the order of 10^{-4} s provided that the initial magnetic fields lie in the range of $10^{14} - 10^{16}$ G. This means that neutron stars are born with magnetic fields of magnetars. Magnetic instabilities occurring at the end of the birth process [Geppert & Rheinhardt(2011)] seems to be the cause of the field decay. The basic assumption in this paper is that there is a radiation reaction process that can convert all radiative energy produced by the field decay into kinetic energy. Neutron stars acquire their high velocities during the decay of their magnetic fields.

2. Birth ultrafast magnetic field decay of neutron stars

The Larmor formula for the power radiated by a time-varying magnetic dipole moment $P = 2\ddot{\mu}^2/(3c^3)$ and the estimate $\ddot{\mu} \sim \mu_0/\tau^2$, where τ is the characteristic time in the exponential field decay law $B(t) = B_0 e^{-t/\tau}$, imply the equation $P \simeq 2\mu_0^2/(3c^3\tau^4)$, which can be used together with the relation $\mu_0 = B_0 R^3/2$ to yield the power radiated by a neutron star of radius R and an initial magnetic field B_0 : $P \simeq B_0^2 R^6 / (6c^3\tau^4)$. Consider

now the specific time τ_s elapsed during the field decay from B_0 to the current surface magnetic field B_s . The condition $B(\tau_s) = B_s$ and the exponential law $B(t) = B_0 e^{-t/\tau}$ imply $B_s = B_0 e^{-\tau_s/\tau}$ and thus $\tau_s = \tau \ln(B_0/B_s)$. During the time τ_s the energy radiated $E_{\text{rad}} \approx \tau_s P$ is given by $E_{\text{rad}} \approx B_0^2 R^6 \ln(B_0/B_s) / (6c^3 \tau^3)$. If this energy is converted into kinetic energy $E_{\text{kin}} = Mv^2/2$ of the neutron star then $B_0^2 R^6 \ln(B_0/B_s) / (6c^3 \tau^3) = Mv^2/2$, which implies $\tau = [B_0^2 R^6 \ln(B_0/B_s) / (3c^3 Mv^2)]^{1/3}$. To get the order of magnitude of τ consider a neutron star with $B_s = 10^{12} \text{G}$ and $v = 400 \text{ km/s}$. If one assumes $B_0 = 1.4 \times 10^{15} \text{G}$ then $\tau \approx 3.3 \times 10^{-5} \text{s} \approx R/c$. This is the theoretical shortest time for accelerating the neutron star. One can adopt the time $\tau = R/c$ as the characteristic time in the law $B(t) = B_0 e^{-t/\tau}$. This adoption implies the specific time $\tau_s = (R/c) \ln(B_0/B_s)$. For the abrupt field decays one has $2.3 \leq \ln(B_0/B_s) \leq 4.4$ and then $\tau_s \sim 10^{-4} \text{s}$, which indicates that the decay from B_0 to B_s is ultrafast if B_0 lies in the range of $10^{14} - 10^{16} \text{G}$. Using $\tau = R/c$ the assumed energy conversion reads $B_0^2 R^3 \ln(B_0/B_s) / 6 = Mv^2/2$. This equation and $v \approx \sqrt{3/2} v_\perp$, $M = 1.4 M_\odot$ and $R = 10 \text{ km}$ implies the following expression the initial magnetic field:

$$B_0 = B_s e^{W(\sigma v_\perp^2 B_s^{-2})/2}, \quad (1)$$

where $\sigma = 2.52 \times 10^{16} \text{gr/cm}^3$ and $W(x)$ is the Lambert function, which is defined as the inverse of the function $f(x) = xe^x$ satisfying $W(x)e^{W(x)} = x$. Remarkably, Eq. (1) predicts the value of B_0 in terms of the current values for v_\perp and B_s of the neutron stars.

3. Applications

As already mentioned, the enigmatic pulsar PSR J2144-3933 exhibits magnetar properties but its magnetic field is typical of radio pulsars: $B_s = 1.9 \times 10^{12} \text{G}$. This pulsar has the transverse velocity $v_\perp = 135 \text{ km/s}$ (Tiengo et al. 2011). In this case Eq. (4) predicts $B_0 \approx 6.29 \times 10^{14} \text{G}$ indicating that this pulsar was born with a magnetic field typical of magnetars. Analogously, the SGR 0418+5729 also exhibits magnetar properties but it has a field of radio pulsar: $B_s \approx 7.5 \times 10^{12} \text{G}$ (Rea et al. 2010). The velocity v_\perp of this pulsar has not been reported yet. It is reasonable to assume that this velocity lies in the range $100 - 400 \text{ km/s}$. If this would be the case, then Eq. (1) predicts that the initial magnetic field SGR 0418+5729 lies in the range $5.4 \times 10^{14} - 1.9 \times 10^{15} \text{G}$ indicating that this SGR was born with an initial magnetic field typical of magnetars.

Equation (1) can be applied to the set of 130 neutron stars whose periods P_s are in the interval: $.02 \text{ s} \leq P_s < 1 \text{ s}$. The values of P_s , B_s and v_\perp are taken from the ATNF Pulsar Catalogue V 1.43 (www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)]. The average values are $\widetilde{B_s} = 1.28 \times 10^{12} \text{G}$ and $\widetilde{v_\perp} = 409.06 \text{ km/s}$. For this set of pulsars, Eq. (1) predicts $\widetilde{B_0} = 1.7 \times 10^{15} \text{G}$. One can also consider the case of the 9 isolated millisecond pulsars in the interval: $.0015 \text{ s} \leq P_s < .009 \text{ s}$. The average values are $\widetilde{B_s} = 2.59 \times 10^8 \text{G}$ and $\widetilde{v_\perp} = 60.11 \text{ km/s}$. For this set, Eq. (1) predicts $\widetilde{B_0} = 1.8 \times 10^{14} \text{G}$. One concludes then that all neutron star are born with magnetic fields of magnetars.

References

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